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Assessing winter storm flow generation by means of permeability of the lithology and hydrological soil processes

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Abstract

In this study two approaches are used to predict winter storm flow coefficients in meso-scale basins ($10\,km^2$ to $1000\,km^2$) with a view to regionalization. The winter storm flow coefficient corresponds to the ratio between rainfall and direct discharge caused by this rainfall. It is basin specific and supposed to give an integrated response to rainfall. The two approaches, which used the permeability of the substratum and soil hydrological processes as basin attributes are compared. The study area is the Rhineland Palatinate and the Grand Duchy of Luxembourg and the study focuses on the Nahe basin and its 16 sub-basins (Rhineland Palatinate). For the comparison, three statistical models were derived by means of regression analysis. The models used the winter storm flow coefficient as the dependent variable in the models; the independent variables were the permeability of the substratum, preliminary derived hydrological soil processes and a combination of both. It is assumed that the permeability and the preliminary derived hydrological soil processes carry different layers of information. Cross-validation and a statistical test were used to determine and evaluate model differences. The cross-validation resulted in a best model performance for the model that used both parameters, followed by the model that used the preliminary hydrological soil processes. From the statistical test it was concluded that the models come from different populations, carrying different information layers. Analysis of the residuals of the models indicated that the permeability and hydrological soil processes did provide complementary information. Simple linear models appeared to perform well in describing the winter storm flow coefficient at the meso-scale when a combination of the permeability of the substratum and soil hydrological processes served as independent parameters.

1 Introduction

Regionalization is a widely used procedure in hydrology (Burn, 1997; Post and Jakeman, 1999; Kokkonen et al., 2003; Croke and Norton, 2004; Merz and Blöschl, 2004; Parajka et al., 2005; Merz et al., 2006), regionalization being defined as the transfer of information from one basin to another (Blöschl and Sivapalan, 1995). Regression analysis is the most widely used regionalization technique, although alternative techniques are also used (Kokkonen et al., 2003). Since a regression needs a dependent and at least one independent variable, the choice of the variables is usually a hydrological variable as dependent and one or several physiographic basin characteristics as independent variables. Mazvimavi (2003) listed the most commonly used physiographic basin characteristics in regression analyses, which are: land use, geology, drainage density and basin area. Pfister et al. (2002) developed a methodology that determines the qualitative behavior of gauged basins with short historical data series with a view to regionalization, using the winter storm flow coefficient, or C-value, as the dependent parameter in a regression analysis. The previously named basin characteristics served as independent parameters. The C-value is defined as the ratio between rainfall and storm flow, is supposed to be basin specific and to have a strong seasonal variability, and should be more or less constant during winter, expressing the saturated state of the basin (Pfister et al., 2002). Uhlenbrook et al. (2004) pointed out that in meso-scale basins processes combine into a more complex way, producing an integrated runoff response to rainfall. In this study, the C-value is supposed to represent this response of meso-scale basins (i.e. basins ranging in size from 10 km^1 to 10^3 km^2; Blöschl, 1996) to rainfall during winter. The impermeability of the substratum was found to be an important basin characteristic in describing the C-value of basins in the Grand Duchy of Luxembourg (Pfister et al., 2002); it will serve in this study as a single independent parameter in a first model, which is based on linear regression. Since soils form the first medium between precipitation and runoff generating processes, they will serve in this study as independent parameters for a second model.

The lithology is supposed to store information on land use, soils, geo-morphological features and drainage patterns. Zumstein et al. (1989) classified the lithology in terms of permeability of the substratum. Scherrer (1996) developed a methodology to assess hydrological processes in soils with a view to regionalization. It is designed to determine hydrological soil processes on the plot and micro-scale and takes into account soil types, slope, land use and macro-porosity to describe the processes. The hydrological processes are limited to the soil (i.e. a maximum of 1.3 m below surface level), incorporating changes in soils as well as recent land use changes. The geology is only taken into account to a certain degree in the derivation of the hydrological soil processes. However, this methodology is time consuming and often, detailed soil data is lacking to apply it on a smaller scale. Therefore, the methodology has been up-scaled using a neural network model developed by Steinrücken et al. (2006) and applied to the Nahe basin, resulting in preliminary modelled hydrological soil processes.

In this study the classification of the permeability of the substratum is limited to three classes: permeable, semi-permeable and impermeable. Processes like weathering, pedogenesis, changes in climate combined with anthropogenic influences are not incorporated within the permeability assessment. Moreover, the scale of available geological maps and more important, the simplification of the lithology into permeability classes puts severe limits to detailed information subtraction on the permeability of the substratum. The modeled hydrological soil processes are: Saturated Overland Flow (SOF), Saturated Subsurface Flow (SSF) and Deep Percolation (DP). SOF and SSF are both represented by three types: 1, 2 and 3 of which 1 is the fastest and 3 the slowest form. The "detailedness" of the hydrological soil processes is supposed to be larger compared to the permeability assessment of the substratum due to a larger scale. Both the permeability of the substratum and the hydrological soil processes will be derived as percentages of total basin areas in a GIS.

The objective of the study is to compare information levels of the simplified permeability of the substratum, the hydrological soil processes and a combination of both with respect to the winter storm flow coefficient. For this purpose three models that are based on regression analysis will be used. Model results will be assed with cross-validation, a statistical test and a comparison of the residuals. The use of the permeability of the substratum as a parameter in a regression model may open possibilities for predictions in un-gauged basins concerning their runoff coefficient and the hydrological soil processes may possibly add more detail to these predictions.

2 Study area

The study area comprises 71 basins located throughout the Grand-Duchy of Luxembourg and the Rhineland Palatinate including the Nahe basin (4011 km^2) and its 16 sub-basins, listed in Table 1. All basins have daily discharge measurements for a period of 30 years (1972–2002). Altitudes range from 67 m a.s.l. at the lowest point of the Rhine valley to 816 m a.s.l. on the Hunsrück middle mountain region. The study area has an oceanic temperate climate in the West transforming to a semi-oceanic climate to the East. The temperate humid climate is influenced by the Atlantic Ocean. The macro relief influences rainfall patterns as well. The average annual precipitation ranges from approximately 540 mm in the middle part of the study area (Rhine valley) to approximately 1100 mm on the higher ridges, with an average annual precipitation of 820 mm for the entire study area. The study area is located mainly in the Rhenish Massif and consists largely of schist, siltstone, sandstone and quartzite of Devonian age. The northeastern part is characterized by tectonic dissections of geological strata, hence displaying a heterogeneous geology in comparison to the remainder of the study area (Sauer et al., 2002). The southeastern part of the study area (Pfalz and Rhine valley) consists of an alternation of sandstone, conglomerates and clay of the Buntsandstein and of Tertiary sandy, silty deposits and Quaternary Rhine terraces. The overall land use of the study area is 4% urban area, 28% cropland, 22% grassland and 46% forest. However, land use percentages vary between meso-scale basins. For the 68 basins, daily discharge series were available from 1972 until 2002. Rainfall for the same period was obtained from 54 meteorological stations located throughout the study area.

In Fig. 1, the permeability of the entire study area is given. In Figs. 2a and b, the permeability and the hydrological soil processes of the Nahe basin and its 16 sub-basins are given.

3 Methodology

As dependent variable in the regression models, the winter storm flow coefficient or C-value will be used. The calculation of the C-values can be summarized as follows: firstly, calculate the storm flow of basins by using a base flow separation technique; secondly, build double mass curves of winter storm flow and winter rainfall for each basin and thirdly, calculate the slope in the double mass curve, which denotes the basin specific winter runoff coefficient C. An extensive description of the derivation of the C-value can be found in Pfister et al. (2002), who used the Grand Duchy of Luxembourg as study area. As stated in the introduction, the C-value is supposed to be basin specific, have a strong seasonal variability and should be more or less constant during winter, expressing the saturated state of the basin (Pfister et al., 2002). The current study focuses on the Nahe basin and its 16 sub-basins, located in the Rhineland Palatinate (Germany) and derives relationships between C-values and permeability on the one hand and C-values and hydrological soil processes on the other hand. The derivation of the models can be described as follows:

1. Derivation of three regression models: I, II and III. The models take the C-values of the Nahe basin and its 16 sub-basins as a dependent variable and:
   (a) Model I takes the percentage of the permeability of the substratum of a basin as an independent variable. To underpin this relationship, 71 basins located throughout the Grand Duchy of Luxembourg and Rhineland Palatinate, including the Nahe basin and its sub basins, will be used in a linear regression with their C-values as dependent and permeability of their substrata as independent variables. Model I will be obtained by linear regression.

(b) Model II takes the percentage of one hydrological soil process or the percentage of a combination of hydrological soil processes of a basin as an independent variable. A Principal Component Analysis (PCA) will be used to determine the process or combination of processes that bears the highest correlation with the C-value. A PCA is a multivariate technique that produces a set of components (variables) called principal components, which are weighted linear contributions of the original variables (Chatfield and Collins, 1980; James and McCulloch, 1990). In this case the original variables are the C-value and the 127 combinations of the seven hydrological soil processes. Model II will also be obtained by linear regression. Model II will also be obtained by linear regression.

(c) Model III takes the above-derived independent parameters and will be obtained by multiple linear regression.

2. Comparing model performances

(a) The performance of the models will be determined with cross-validation, using the RMSE as a comparator value.

(b) The non-parametric Kruskal-Wallis H test (Kruskal and Wallis, 1952) will be used to decide if there is a significant difference between the derived regression models.

(c) The residuals of the models will be compared in order to determine internal mutual differences.

The preliminary models I–III are given in Eqs. (1–3):

$$\mathbf{C_I} = a \cdot [\mathbf{permperc}] + b \tag{1}$$

$$\mathbf{C_{II}} = c \cdot [\mathbf{hsp}] + d \tag{2}$$

$$\mathbf{C_{III}} = e \cdot [\mathbf{permperc}] + f \cdot [\mathbf{hsp}] + g \tag{3}$$

Where: C_I, C_{II}, C_{III} are the modeled runoff coefficients of a basin [–]
a, b, c, d, e, f and g are constants [–]
permperc is the percentage of permeable substratum of a basin [–]
hsp is the percentage of the hydrological soil process(es) mostly linked to the C-value of a basin [–]

4 Results and discussion

The relation between C-values and the percentage of impermeable substratum in the 71 basins of the Rhineland Palatinate and the Grand Duchy of Luxembourg showed a good correlation. It could very well be described as linear with an R^2 of 0.79 (Fig. 3a). When using a linear regression to model the winter storm flow coefficient of the 71 basins, the residuals did not indicate a bias (Fig. 3c), justifying the relationship. These results were also in agreement with the findings of Pfister et al. (2002) for basins located in the Grand Duchy of Luxembourg concerning basin-specific, more or less stable winter storm flow coefficients. Pfister et al. (2002) also found a strong relationship between winter storm flow coefficients and the permeability of the substratum. Apparently, the winter storm flow coefficient appeared to be a good general descriptor of the saturated state of meso-scale basins and well suited to act as a hydrological variable to be used in regionalization procedures.

In Table 1, the calculated C-values and standard deviations of the Nahe basin and its 16 sub-basins are listed with their basin size. The correlation between C-values and permeability was less clear for the Nahe basin and its 16 sub-basins than that for the entire study area: an R^2 of only 0.58 was obtained (Fig. 4a).

The linear regression between the C-values of the Nahe basin and its 16 sub-basins and the percentage of impermeable substratum resulted in model I and is given in Eq. (4). The residuals of model I did not indicate a bias (Fig. 4b).

$$\mathbf{C_I} = 0.865 \cdot [\mathbf{permperc}] - 0.043 \tag{4}$$

The PCA determined that the correlation between the C-value and the sum of the hydrological soil processes SSF1, SSF2 and SSF3 was the strongest out of the 127 possible combinations for the Nahe basin and its 16 sub-basins. This correlation had an R^2 of 0.74 and was remarkably better than the previous one (Fig. 4c). A linear regression between these variables resulted in model II, which had the C-value as dependent variable and the sum of SSF1, SSF2 and SSF3 as an independent variable. Model II is given in Eq. (5):

$$\mathbf{C_{II}} = 1.728 \cdot [\mathbf{SSF1} + \mathbf{SSF2} + \mathbf{SSF3}] - 0.071 \quad (5)$$

Where: SSF1, SSF2 and SSF3 are the area percentages of the respective hydrological soil processes of a basin [–]

The residuals of model II showed no bias (Fig. 4d).

The more or less constant C-value during winter indicated a saturated state of the basins; therefore, presumably a large amount of the soils of the basins should also be saturated. The good correlation between the C-values and the sum of the saturated subsurface flow processes, as derived from the PCA, could therefore be explained that during winter when the C-value is calculated, the saturated subsurface flow processes reflected the saturated state of the basins. However, since the C-value can take per definition only values between 0 and 1, extrapolating the winter storm flow coefficient of model II when the surface area of the hydrological soil processes becomes larger than 60%, becomes problematic (Fig. 4c), while this is not the case for model I. Lack of basins with high enough percentages of the SSF1, 2 and 3 processes prevents making assumptions on its behavior concerning the winter storm flow coefficient.

When the variables that have been used in the models I and II (i.e. the permeability of the substratum and the sum of the hydrological soil processes SSF1, SSF2 and SSF3) were used in a multiple linear regression, model III was obtained and is given in Eq. (6):

$$\mathbf{C_{III}} = 0.334 \cdot [\mathbf{permperc}] + 1.308 \cdot [\mathbf{SSF1} + \mathbf{SSF2} + \mathbf{SSF3}] - 0.104 \quad (6)$$

Figure 5a depicts the correlation between the modeled winter storm flow coefficients by model III and the calculated winter storm flow coefficients. Model III did capture the calculation of the winter storm flow coefficient rather well (R^2 of 0.79). In Fig. 5b the residuals are given, which did not show a bias.

Table 2 lists the Root Mean Squared Errors (RMSEs) of the cross-validated (leave one out method) models. Model III performed best and model I performed worst. The differences between the model performances were considerable, especially between model I and the models II and III. The slight gain in model performance for model II compared to model I indicated that the parameters of the models I and II did possess complementary information. It can be argued for that the effort to obtain extra information on the hydrological soil processes pays off against a considerable increase in model performance (i.e. performance of model I against performance of model III). However, the question remains whether with a better assessment of the geology by using more detailed geological maps, a much better performance of model I could have been achieved, rendering the hydrological soil processes superfluous.

In order to see if the three models I, II and III differed substantially (H_0 hypothesis: they are not from the same population), the nonparametric Kruskal-Wallis H test (Kruskal and Wallis, 1952) was applied. The test clearly indicated an acceptance of the H_0 hypothesis, which means that it can safely be assumed that the difference between the samples (i.e. the modeled values of each model) reflected a real difference between the used models, thus indicating that the three models did possess different information levels. In Table 3, the residuals for all three models are given to compare internal mutual differences.

It turned out that for the models I and II the five worst performing basins were in four cases not the same. This indicated that for these basins the information level between the lithology assessment and the soil hydrological processes assessment was apparent. The lithology of the Kallenfels basin, the worst performing basin of model I, consists of predominantly claystone and siltstone with inclusion of sandstone (geological formation of the Hunsrückschiefer). In this analysis it was classified as impermeable bedrock (based on the assumption that schist is an impermeable bedrock). Nevertheless, the inclusions of sandstone, which support sandy soils, allow for deep percolation and were not exactly known in this study. Also, a weathered zone or saprolite could have been developed at the surface, just beneath the soil, making storage of water possible. The hydrological soil processes indicated DP and SSF3 for large areas of the as impermeable classified substratum of the Kallenfels basin; therefore, this area was probably assessed as too large in the permeability assessment. The same was the case for the Obermoschel and Odenbach basins. In both basins, various areas consisted of the lower Glan-subgroup, which is an alternation of predominantly grey, partly red clay with inclusions of silt- and sandstone. In the permeability assessment these areas have been classified as impermeable, but could well have been assessed as permeable due to their sandstone inclusions. Large areas of DP and SSF3 indicated by the hydrological soil processes again reflected this. A rise of their percentage of permeable area could therefore well be argued for. For the least performing basins of model II, similar explanations for the assessment of the hydrological soil processes as for the assessment of the permeability could be found, which means that the hydrological soil processes were assessed as being too large or too small. Since the assessment of the hydrological soil processes stops at maximum 2 m below surface level, deeper lying impermeable substrata are not always taken into account when assessing the hydrological soil processes. This means that a permeable soil on top of deeper lying impermeable bedrock could still result in SSF.

5 Conclusions

Simple linear models performed rather well to describe runoff-producing processes during winter at the meso-scale. The winter storm flow coefficient could be used as a dependent parameter in a regression analysis. Model performance using a cross validated RMSE indicated that the simplest model with only one simplified independent parameter (i.e. the permeability of the substratum) performed less well than the model that took into account a more complex independent parameter (i.e. the sum of saturated subsurface flows as a hydrological soil process). However, when a linear regression model was used, which combined both parameters this model performed best. The previously described parameters may perhaps be used for predictions in un-gauged basins.

The non-parametric Kruskal and Wallis test that was used to test if the models differ substantially gave a negative result, which indicated that the models came form different populations, carrying different levels of information. Comparison of the residuals of the models indicated that badly modeled basins by using the permeability of the substratum as an independent parameter were explained by a lack of information in the permeability of those basins, which could be provided by the preliminary hydrological soil processes. Badly modeled basins by using a linear combination of hydrological soil processes as an independent parameter were partly explained by a lack of information in the assessment of the hydrological soil processes. This information could be provided by the permeability. As a consequence, the third model that combined both permeability and the hydrological soil processes performed better than the other models. To obtain extra information on the hydrological soil processes paid off against a considerable increase in model performance. However, with a better assessment of the geology by using more detailed geological maps, a much better performance of model I might have been achieved. Using the permeability as a linear estimator for the C-value in combination with hydrological soil processes could determine the winter storm flow coefficient and thereby runoff production areas very well. Testing the approach with better geological maps and for other regions with a different climate and landscape remains the objective of further study.

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Table 1. C-values and standard deviations of the 16 sub-basins of the Nahe basin for a period from 1972 until 2002 and basin size.

Basin name	Basin number [–]	C-value [–]	St dev [–]	Basin size [km^2]
Altenbamberg	4	0.29	0.09	318
Boos	16	0.50	0.12	2833
Enzweiler	13	0.74	0.14	22.7
Eschenau	10	0.51	0.10	605
Gensingen	17	0.16	0.06	197
Grolsheim	14	0.50	0.14	4011
Heddesheim	3	0.68	0.15	166
Imsweiler	8	0.37	0.11	172
Kallenfels	12	0.46	0.11	253
Kellenbach	2	0.52	0.16	362
Kronweiler	15	0.86	0.10	65
Nanzdietschweiler	11	0.47	0.12	195
Obermoschel	5	0.37	0.11	62
Odenbach	7	0.5	0.11	85
Odenbach Glan	6	0.44	0.11	1069
Steinbach	1	0.3	0.16	46
Untersulzbach	9	0.21	0.06	217

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Table 2. The RMSE of the cross-validated models I, II and III.

	Model I	Model II	Model III
RMSE	0.114	0.089	0.081

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Table 3. Residuals of the three Nahe models: the five worst performing basins of each model are given in bold.

Basin name	Residuals model I [–]	Residuals model II [–]	Residuals model III [–]
Altenbamberg	–0.030	–0.159	–0.111
Boos	0.025	–0.010	–0.004
Enzweiler	0.109	–0.095	–0.074
Eschenau	0.080	0.096	0.095
Gensingen	–0.220	–0.045	–0.072
Grolsheim	0.109	0.072	0.083
Heddesheim	0.118	0.011	0.020
Imsweiler	0.033	–0.013	0.014
Kallenfels	–0.223	–0.052	–0.120
Kellenbach	–0.059	0.078	0.032
Kronweiler	0.194	0.153	0.146
Nanzdietsweiler	0.072	0.114	0.114
Obermoschel	–0.131	–0.077	–0.094
Odenbach	–0.105	0.070	0.012
Odenbach Glan	0.025	0.032	0.037
Steinbach	–0.020	–0.165	–0.113
Unterzultsbach	0.020	–0.002	0.041

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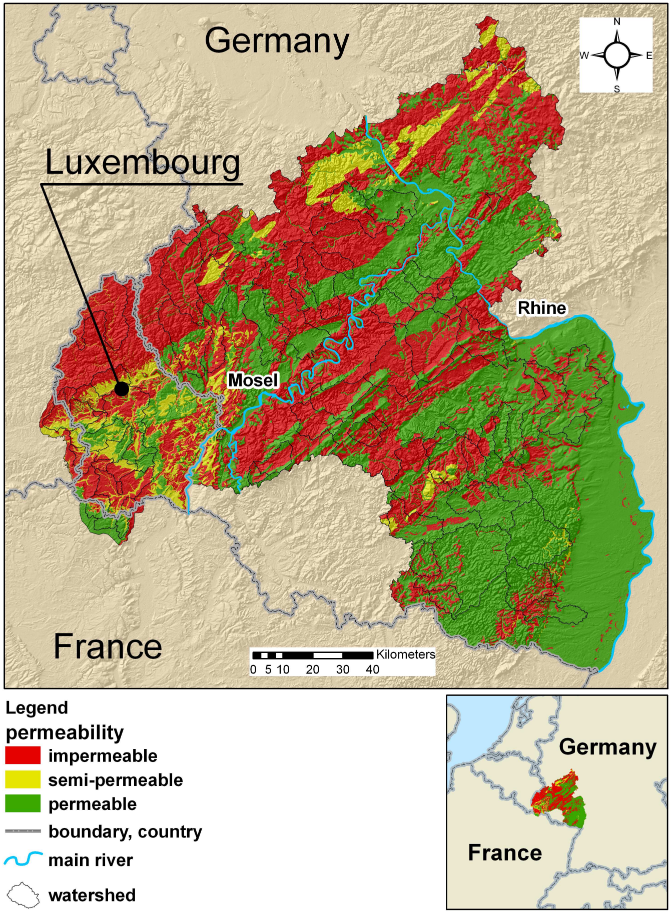

Fig. 1. Permeability map of the Rhineland Palatinate and the Grand Duchy of Luxembourg.

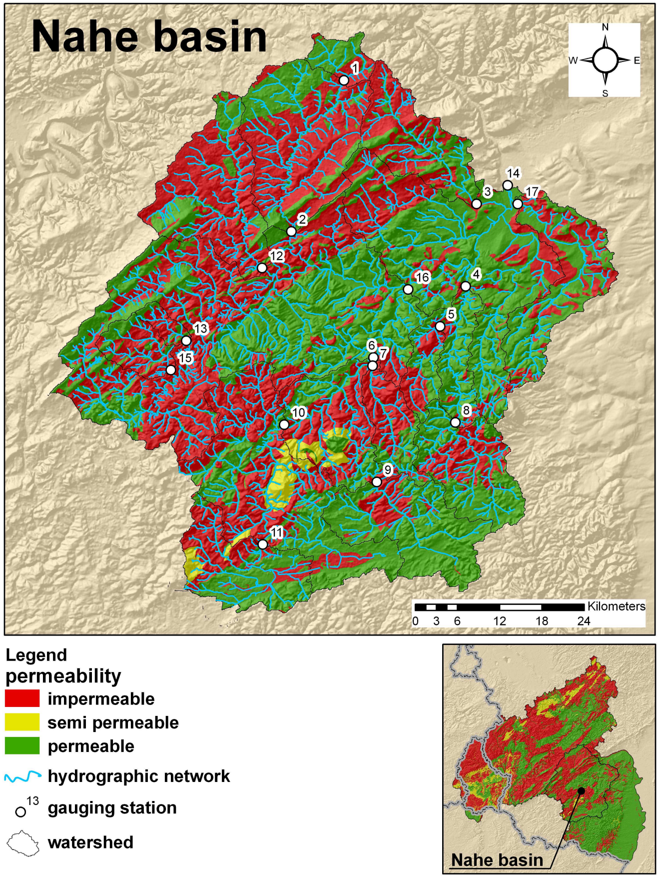

Fig. 2a. Permeability map of the substratum of the Nahe basin and its 16 sub-basins. For the basin numbers see Table 1.

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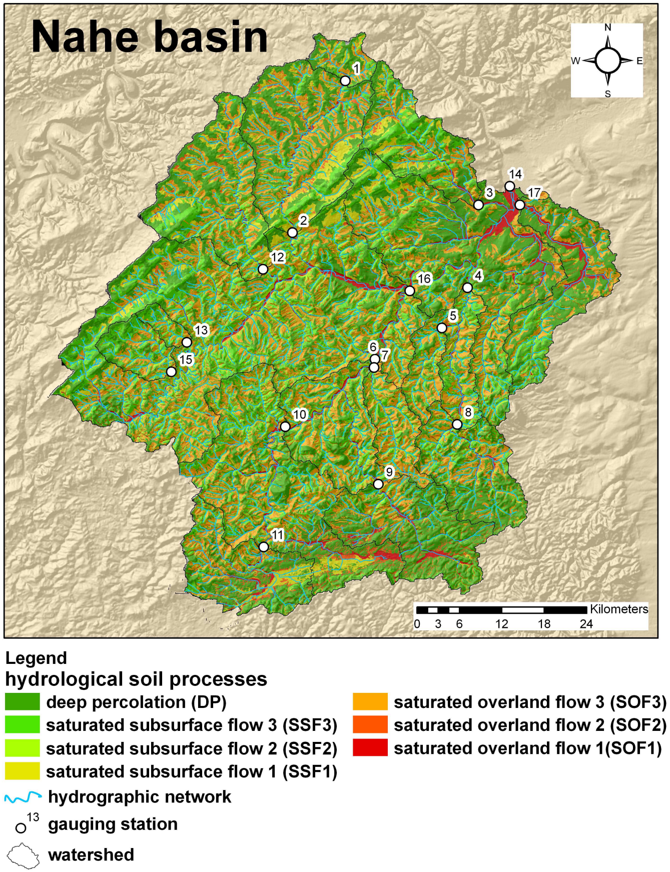
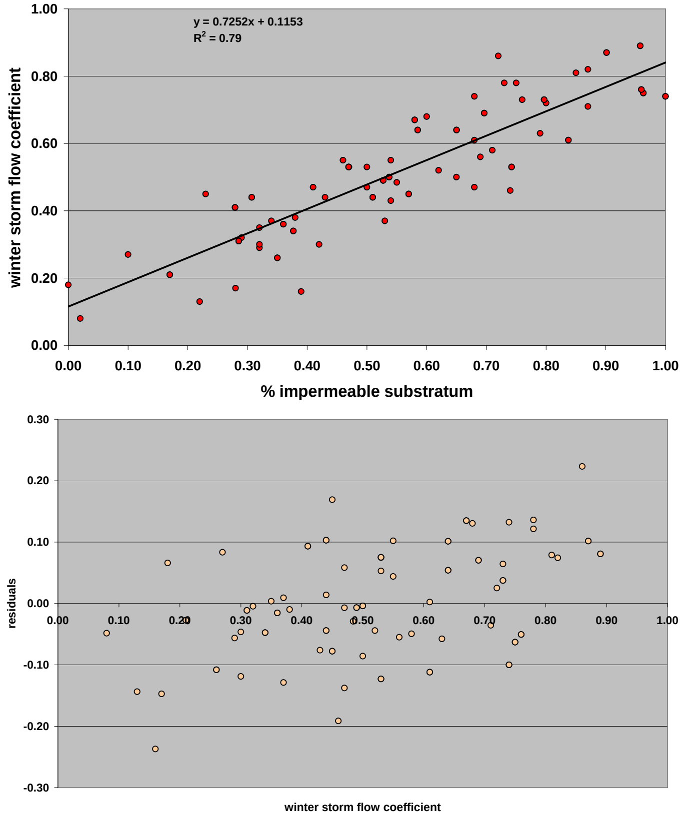


Fig. 2b. Preliminary hydrological soil processes map of the Nahe basin and its 16 sub-basins (after Steinrücken et al., 2006). For the basin numbers see Table 1.



(a)

(b)

Fig. 3. **(a)** correlation between winter storm flow coefficient and percentage of impermeable substratum of Rhineland Palatinate and Luxembourg basins, **(b)** residuals of this relation.

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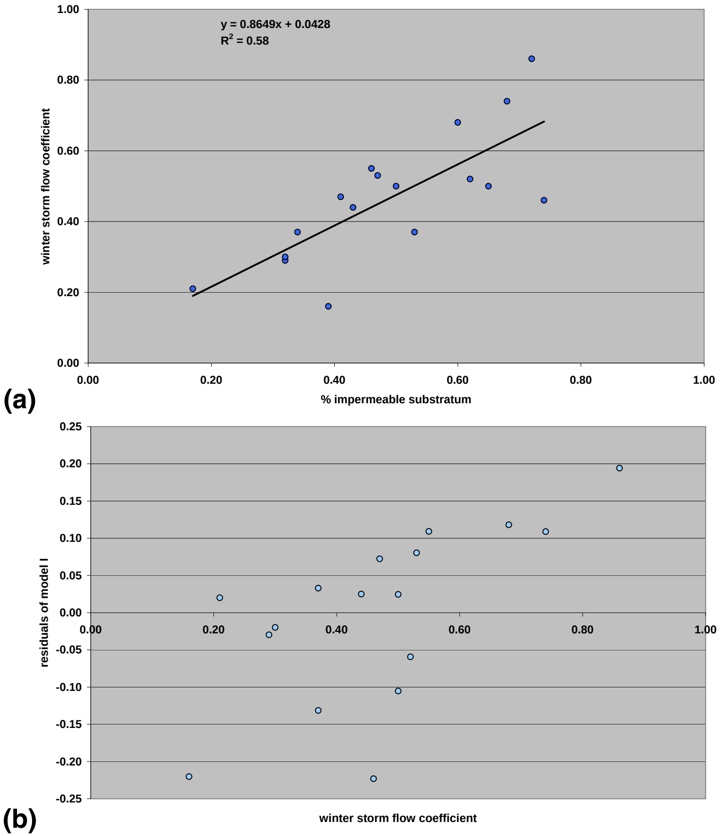

Fig. 4. (a) correlation between the percentage of impermeable substratum and the C-value for the Naghe basins and its 16 sub-basins, **(b)** residuals of model I for the Nahe basins and its 16 sub-basins.

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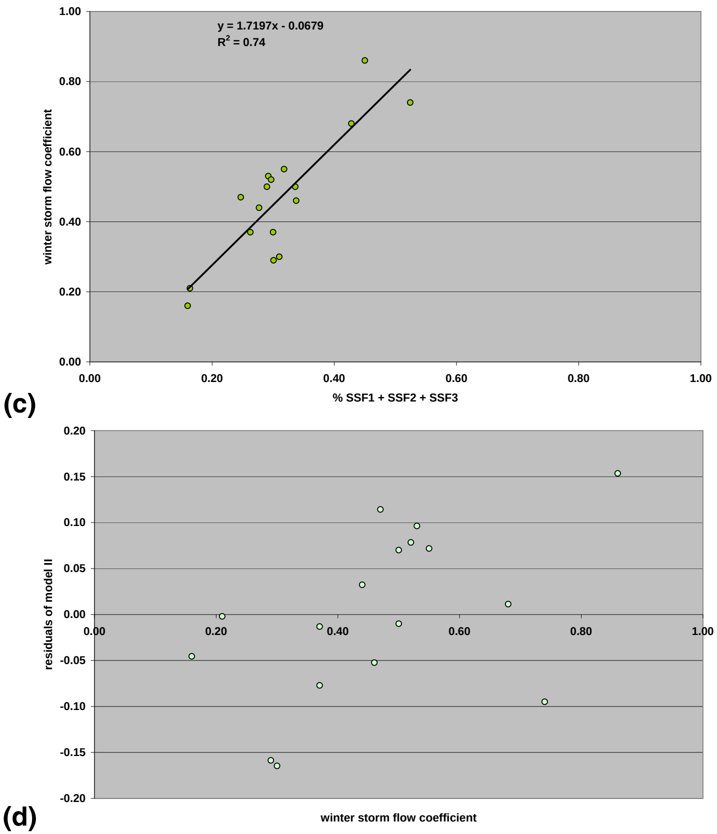

Fig. 4. **(c)** correlation between the percentages of SSF1, SSF2 and SSF3 and C-value for the Nahe basin and its 16 sub-basins, **(d)** residuals of model II for the Nahe basin and its 16 sub-basins.

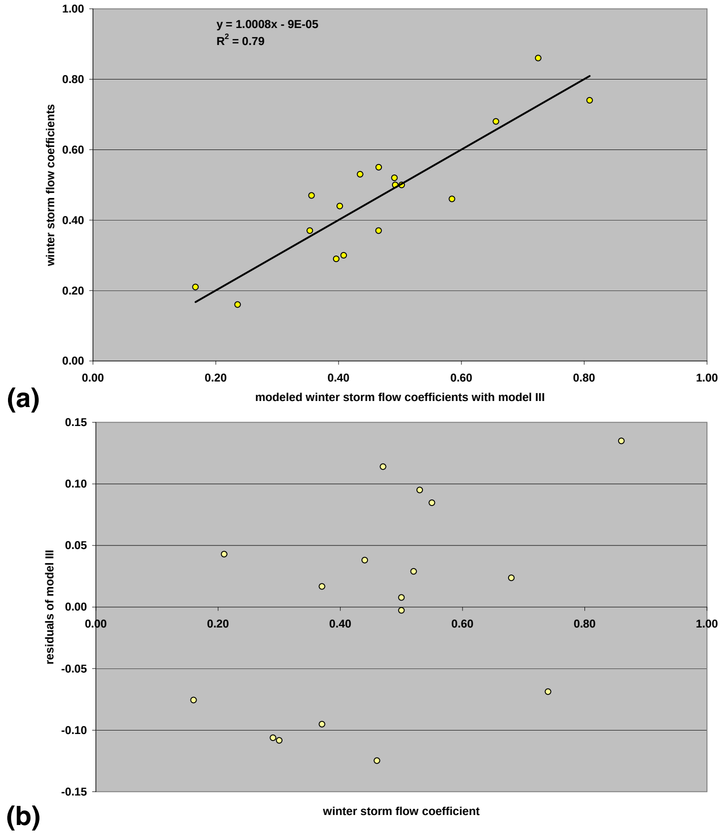

Fig. 5. **(a)** correlation between C-value and model III, **(b)** residuals between modeled and measured winter storm flow coefficients.